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TECHNICAL NOTE

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THE DETERMINATION OF ABLATIVE PROPERTIES

OF MATERIALS IN FREE-FLIGHT RANGES

By Raymond C. Savin, Hermilo R. Gloria,
and Richard G. Dahms

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Moffett Field, Calif.

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THE DETERMINATION OF ABLATIVE PROPERTIES OF MATERIALS IN FREE-FLIGHT RANGES[1]

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SUMMARY

The laboratory technique described provides test conditions of high heating rates at high stagnation enthalpy potential. Small ballistic models are launched at velocities above about 15,000 ft/sec and caught after they decelerate to about 1,000 ft/sec. For the experimental results presented, the models were machined from thermoplastic materials. The measured mass losses due to ablation are combined with analytical results to deduce intrinsic heat capacities and vapor shielding effectiveness of the test materials. These properties are then employed to calculate effective heats of ablation.

INTRODUCTION

Ballistic ranges are used by many research groups to study aerodynamic forces and moments on models. It is not generally recognized that these facilities also can be used to study properties of materials under conditions similar to those encountered by thermal protective systems of atmosphere entry vehicles. The purpose of this report is to describe the laboratory technique developed for use in the Ames Atmosphere Entry Simulator (ref. 1). An experimental investigation is described in which mass losses due to ablation were measured for a group of thermoplastics. The experimental results are combined with analytical results to obtain the ablative properties of these materials.

SYMBOLS

h	specific enthalpy, Btu/lb
H_A	intrinsic heat capacity, Btu/lb
H_{eff}	effective heat of ablation, $\frac{\dot{q}_o}{\dot{m}}$, Btu/lb

[1]This paper is the unclassified portion of NASA TM X-397 entitled "Ablative Properties of Thermoplastics Under Conditions Simulating Atmosphere Entry of Ballistic Missiles" by Raymond C. Savin, Hermilo R. Gloria, and Richard G. Dahms, 1960.

m mass of model, lb

$\dot{m}$ mass rate of ablation, lb/ft^2-sec

$\dot{q}_o$ aerodynamic convective heating rate to a nonablating surface at ablation temperature, Btu/ft^2-sec

S face area of model, ft^2

t time, sec

η transpiration factor

μ ratio of molecular weights of air to injected vapor

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Subscripts

e edge of boundary layer

L laminar flow

sub subsonic flow

sup supersonic flow

t stagnation point

T turbulent flow

w wall

EXPERIMENTAL PROCEDURE AND DATA REDUCTION

The data to be discussed were obtained in the Ames Atmosphere Entry Simulator. In this facility, models are launched through air expanded through a supersonic nozzle to produce an exponential variation in density with distance corresponding to the variation with altitude in the atmosphere. This nozzle was designed for the simulation of the motion and heating of full-scale reentry vehicles with small-scale test models. For the present tests, the criteria of importance are the speed and heating histories of the model and its total weight loss due to ablation. For this purpose, the test channel could also have been a ballistics range.

The test models were machined from the following five thermoplastic materials:

Polytetrafluoroethylene (Teflon)
Ceramic-reinforced teflon (Fluorogreen-T)
Ethyl cellulose (Blue ethocel)
Polycarbonate (Lexan)
High-density polyethylene (Fortiflex)

The model shape employed in this investigation consisted of a spherically tipped cone-cylinder with a cone half-angle of 60°. The tip radius was equal to one-fourth the afterbody diameter of 0.788 inch. The afterbody length was selected (depending on the material) to maintain a weight of 6.1 grams for each model. Detailed dimensions of the test models are given in figure 1.

In the tests, the spherically tipped cone-cylinder models were launched at initial or entry speeds (relative to the air stream) varying from approximately 13,000 to about 20,000 ft/sec. Time-distance histories of each model flight were determined by means of photobeam detectors and electronic counters as described in reference 1. Models were recovered at the end of their flight after impacting into sponge rubber at about 1,000 to 1,500 ft/sec.

To determine the total weight losses experienced, the models were weighed and measured before launching and after recovery. The launching weight loss was then subtracted from the total weight loss to determine the weight loss due to ablation over the model face. The weight lost during launch was determined from the decrement in afterbody diameter (due to launch tube scraping) and from the material density. The lengths and diameters of the models were determined to ± 0.0002 inch before and after each test. Model weights were determined to ± 0.0005 gram before and after each test. These limits in measuring accuracy result in a maximum probable error in weight loss due to ablation of ± 10 percent. In general, the ablation weight losses were about 50 to 60 percent of the total weight losses.

RESULTS AND DISCUSSION

Experimental Results

The recession of the surfaces due to ablation over the faces of recovered models is shown in figure 2 for all the test materials. The solid lines in these photographs represent the profiles of models prior to launching; whereas the shaded portions are silhouettes of the models after flight through the simulator. The area between the solid line and the shaded region represents the distribution of ablated thickness over the faces of models launched at about 15,000 ft/sec. The important thing to note from figure 2 is that, in general, the thickness of ablated material tends to increase with distance downstream of the stagnation point. This type of distribution (see also ref. 1) indicates the presence of transition from laminar to turbulent flow in view of the higher heating rates associated with a turbulent boundary layer (see, e.g., refs. 2 and 3). The total amount of mass lost as a result of ablation, expressed as a percentage of the initial mass of the model, is shown as a function of entry velocity in figure 3. These results will now be used to determine the ablative properties of the test materials.

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Effective Heat of Ablation for Sublimation

It has been shown analytically (see, e.g., ref. 4) that the effective heat of ablation of materials which primarily sublime (i.e., materials which ablate by essentially complete vaporization) can be expressed as a linear function of the enthalpy potential across the boundary layer;[2] namely,

$$H_{eff} = \frac{\dot{q}_o}{\dot{m}} = H_A + \eta(h_e - h_w) \qquad (1)$$

In the above expression, $\dot{q}_o$ is the aerodynamic convective heating rate to a nonablating surface at the ablation temperature, and $\dot{m}$ is the mass rate of vaporization. The term H_A represents the sum of the latent heat of vaporization and the heat absorbed by the solid material in raising the temperature from the initial value up to the vaporization temperature. The quantity H_A then represents the intrinsic heat capacity of the ablative material. The last term in equation (1) represents the "shielding" or "blocking" effect of the vapor given off. The transpiration factor η is a function of the molecular weight of the vapor and of the type of boundary-layer flow.

Expressions for η have been obtained from correlations of transpiration cooling results for various mass injections and for various types of boundary-layer flows. For a three-dimensional laminar boundary layer, Hidalgo (ref. 3) obtained the semiempirical relation

$$\eta_L = \frac{3}{5}\,\mu^{1/4} \qquad (2)$$

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[2] This statement holds only for the case where radiative heating can be neglected which is sufficient for the purpose of this paper. For a discussion of the effects of combustion as well as radiation, see references 5 and 6.

where μ is the ratio of molecular weights of air to the injected vapor. For turbulent boundary layers, transpiration data obtained on cones by Pappas and Okuno (ref. 7) were correlated by Hidalgo who derived the expression

$$(\eta_T)_{sup} = \frac{1}{5}\,\mu^{1/3} \tag{3}$$

for the case where the local flow is supersonic. For the case of local subsonic turbulent flow, the data of reference 7 were correlated by Hamaker (ref. 1) and resulted in the relation

$$(\eta_T)_{sub} = \frac{3}{5}\,\mu^{3/5} \tag{4}$$

It can be seen from expressions (1) through (4) that if the intrinsic heat capacity H_A and molecular weight ratio μ are known for a material, its effective heat of ablation can be determined for several types of boundary-layer flows. These relations will now be employed in combination with the previously discussed test results to deduce H_A and μ for the test materials.

Determination of Intrinsic Heat Capacities and Molecular Weight Ratios for Test Materials

The fraction of initial mass lost as a result of ablation over the face of a test model for a particular test trajectory can be calculated from the relation

$$\frac{\Delta m}{m} = \frac{1}{m}\int_0^t\int_S \frac{\dot{q}_o}{H_{eff}}\,dS\,dt \tag{5}$$

where $\dot{q}_o$ is the local convective aerodynamic heat input, S is the model face area, and t is the time of flight. In the calculations, transition from laminar to turbulent flow was located over the spherical tip of the model on the basis of figure 2. Therefore, the ratio of local to stagnation heat flux over this portion of the model was determined as suggested by Lees in reference 2. The boundary layer on the conical portion was probably fully turbulent so that in this region the heat flux was taken to vary inversely as the 1/5 power of the distance. The stagnation heat flux was calculated from the results of Kemp and Riddell (ref. 8). Since the test materials have relatively low vaporization temperatures (about 1000° F), the wall enthalpy, h_w, was neglected in calculating local values of H_{eff} from equation (1). Also, at the cone-cylinder juncture, the enthalpy at the edge of the boundary layer h_e was found to be about 95 percent of the stagnation enthalpy so that h_e was taken equal to the stagnation value. With these considerations, equation (5) takes the form

$$\frac{\Delta m}{m} = \frac{1}{m} \int_0^t \int_S \frac{\dot{q}_o}{H_A + (\eta_T)_{sub} h_t} \, dS \, dt \tag{6}$$

where $(\eta_T)_{sub}$ is employed since the local flow is turbulent and subsonic. For each test material, the mass loss was calculated according to expression (6) for several entry velocities over the range of test conditions. Through the integrations for various combinations of H_A and $(\eta_T)_{sub}$, various curves of mass loss as a function of stagnation enthalpy at entry were obtained and compared with the experimental results. The curve which gave the best fit to the experimental data for each material is shown in figure 4 for all the test materials. The values of H_A and $(\eta_T)_{sub}$ which define each curve and hence represent the properties of the material are also shown.

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From the values of $(\eta_T)_{sub}$ presented in figure 4, corresponding values of μ were determined from equation (4). From the values of μ thus obtained, corresponding values of η_L and $(\eta_T)_{sup}$ were calculated from relations (2) and (3), respectively. These properties are given in the table below for each test material.

Test material	Intrinsic heat capacity, H_A, Btu/lb	Molecular weight ratio, μ	Transpiration factors		
			η_L	$(\eta_T)_{sub}$	$(\eta_T)_{sup}$
Ceramic teflon	550	0.043	0.27	0.09	0.07
Teflon	750	.175	.40	.21	.11
Ethyl cellulose	1000	.428	.50	.36	.15
Polycarbonate	1250	.428	.50	.36	.15
Polyethylene	2000	.428	.50	.36	.15

Values of $(\eta_T)_{sup}$ are approximately one-third of η_L as predicted in reference 5. The effective heats of ablation for the test materials can now be calculated from the properties listed in the above table and equation (1) for three types of flows; namely, laminar flow, subsonic turbulent flow, and supersonic turbulent flow.

Comparisons With Arc Jet Measurements

Ablation properties determined in high-enthalpy arc jets are measured in such low-density streams that the flow must be considered laminar. In contrast, the present data are for turbulent boundary-layer flow. However, the laminar values listed above can be used to compare the present data with arc jet results. The stagnation point values (laminar) of effective heats of ablation from the present tests and from arc jet measurements of Teflon are shown as a function of stagnation enthalpy potential in figure 5. All the results for Teflon are in reasonable agreement. Insofar as the measurements in the two types of facilities are accurate, it appears that equations (1) through (4) can be used for correlating the transpiration factor for different types of boundary-layer flow.

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Moffett Field, Calif., Mar. 29, 1962

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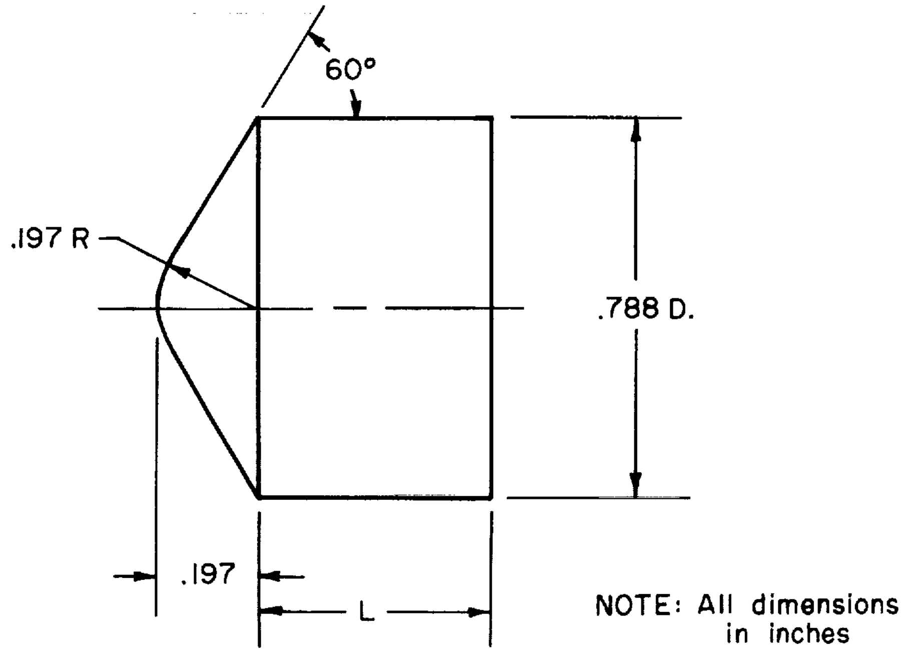

Model weight = 6.1 grams

Material	L
Ceramic teflon	.263
Teflon	.281
Polycarbonate	.569
Ethyl cellulose	.628
Polyethylene	.722

Figure 1.- Test models.

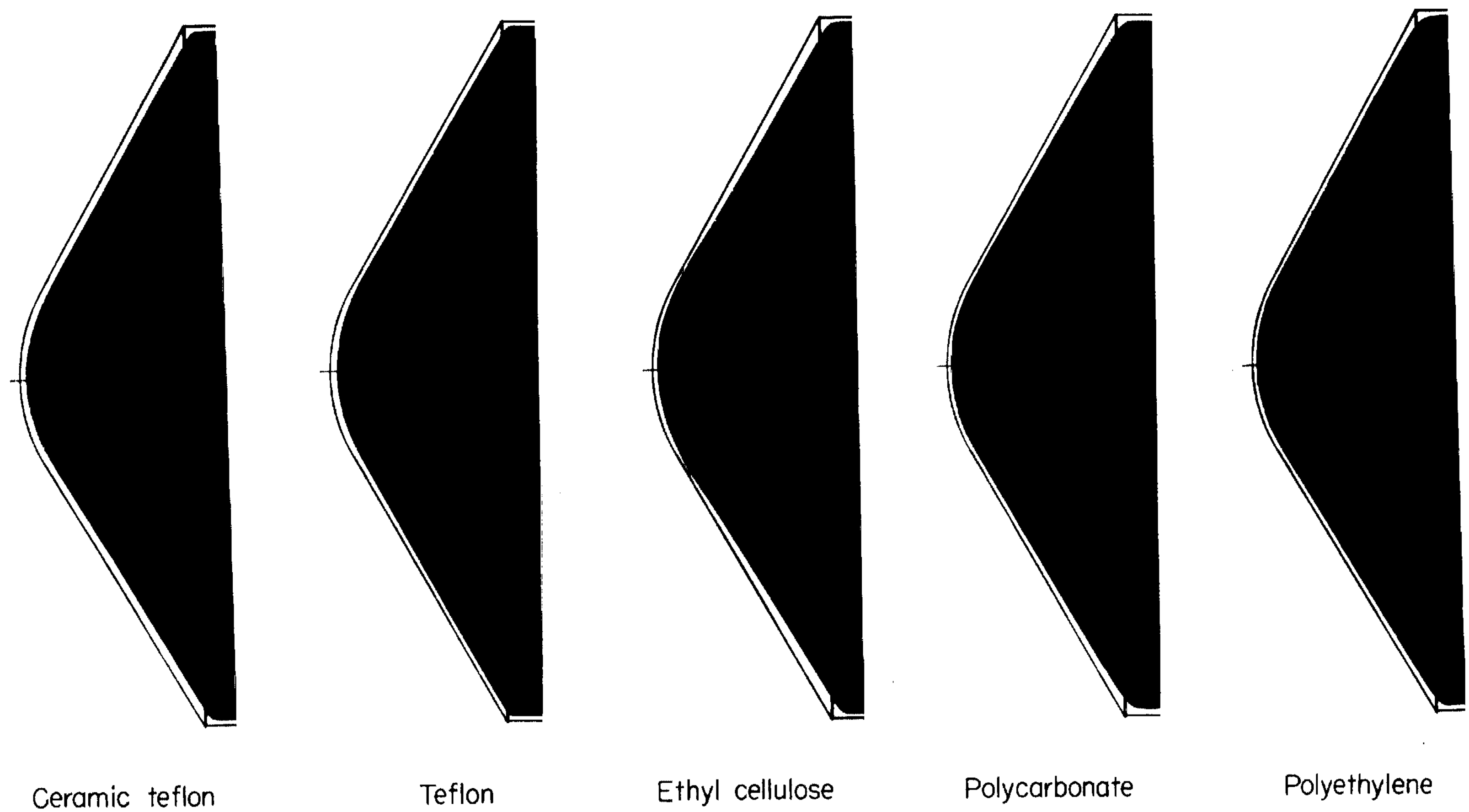

Figure 2.- Distribution of ablated thickness for $V_E \approx 15{,}000$ ft/sec.

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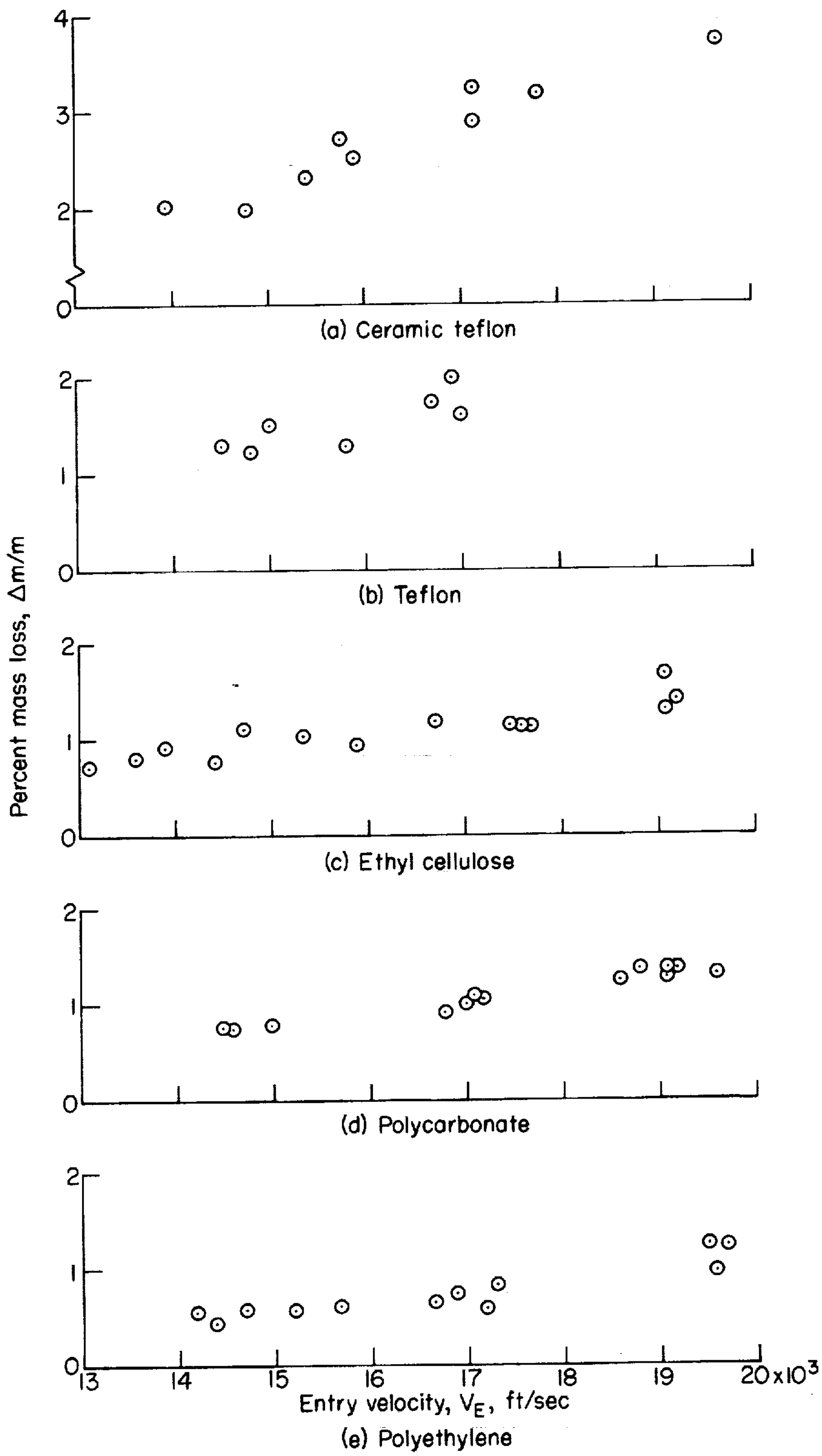

Figure 3.- Variation of mass loss with entry velocity.

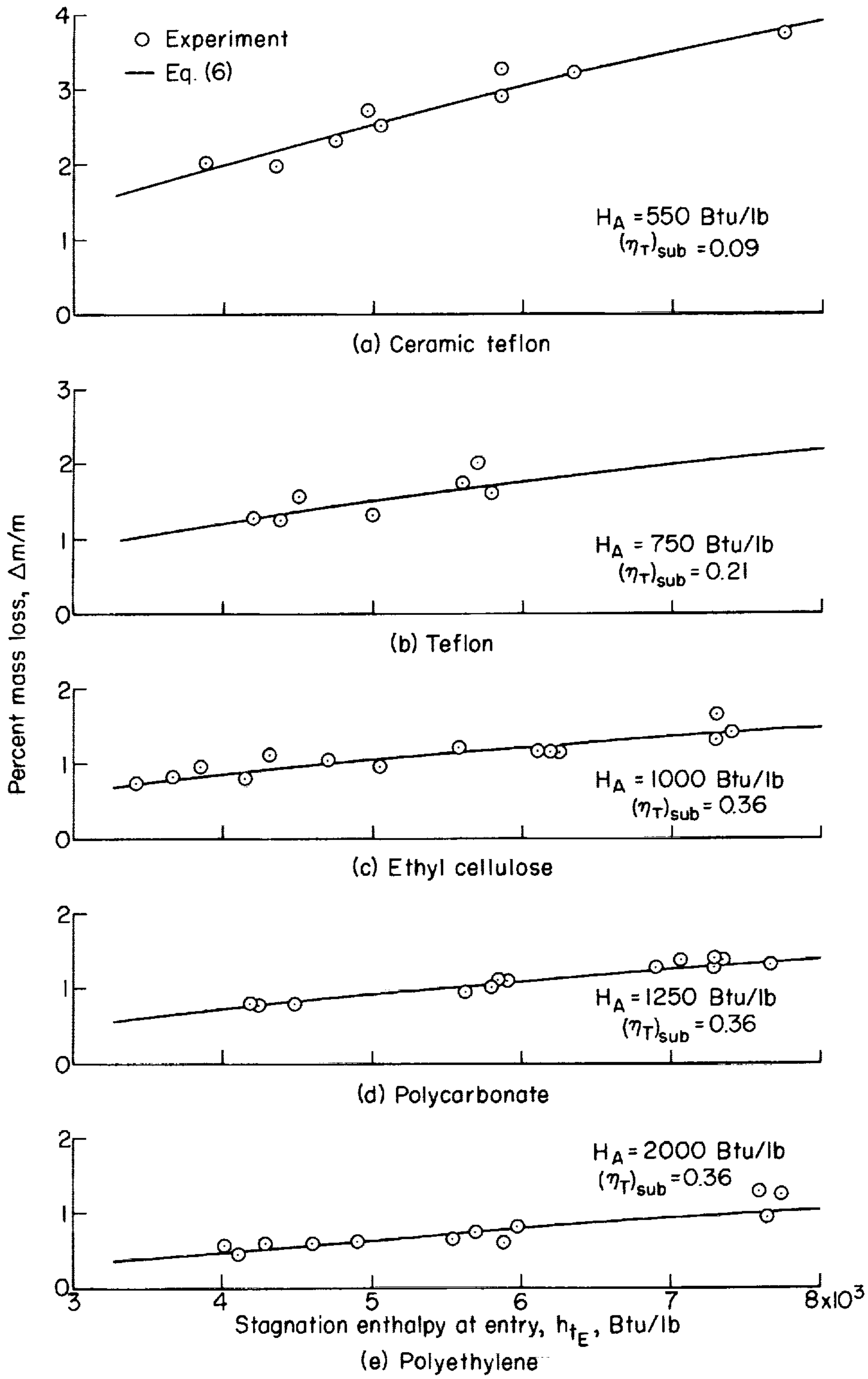

Figure 4.- Variation of experimental and calculated ablation mass losses with stagnation enthalpy at entry.

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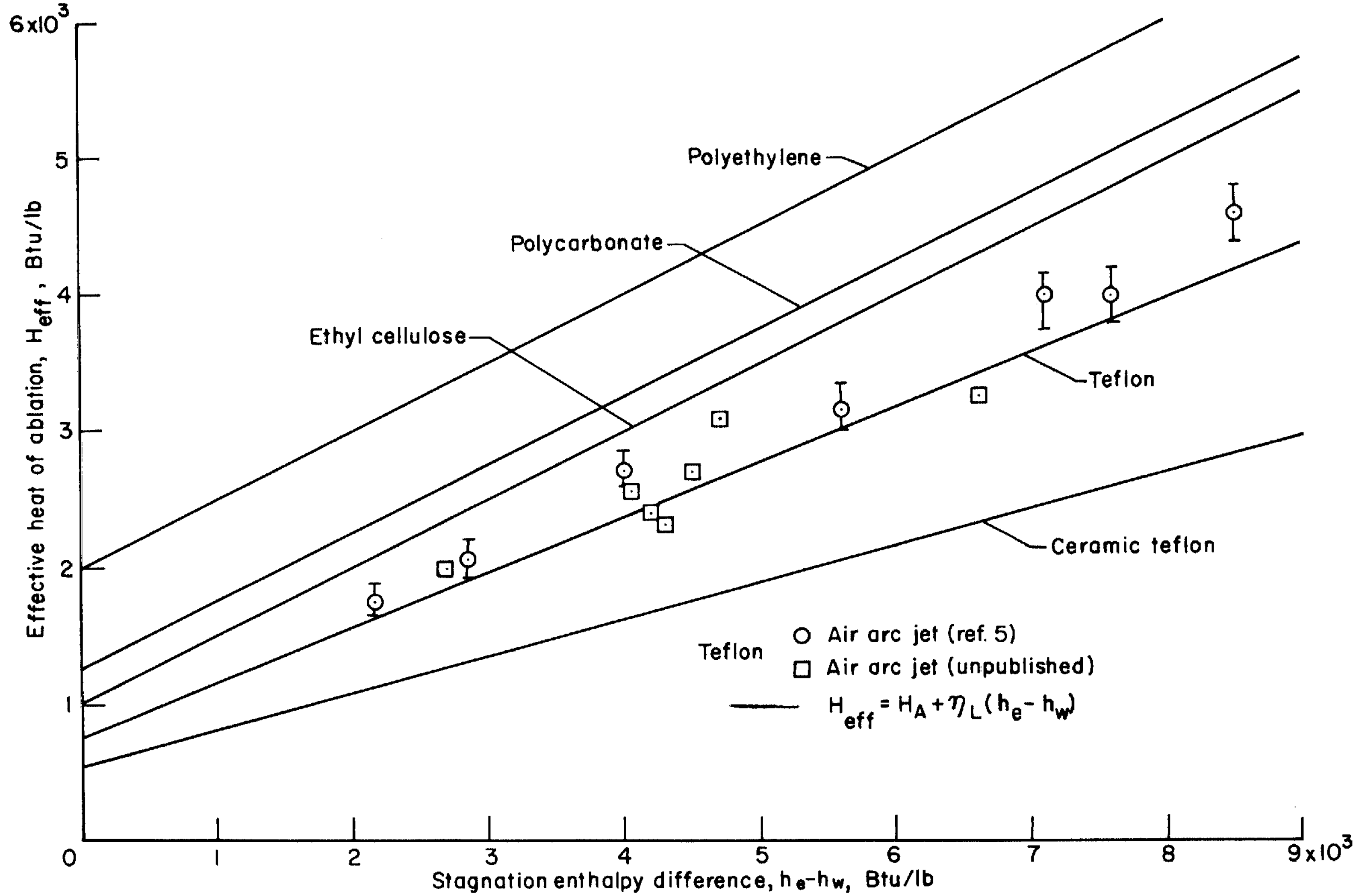

Figure 5.- Effective heats of ablation for a stagnation point.

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